Effects from High Power Microwave Illumination

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Introduction

The effects of high power microwaves (HPM) can be spectacular. It has been reported that ordinary light bulbs have been exploded by 5 kW of UHF power (~400 MHz) radiated from the open end of a 6 × 15" rectangular waveguide (power density ≤ 4 kW/m^2).[1] Other effects observed in this experiment include the lighting of fluorescent lamps at some distance from the waveguide opening and the explosion of steel wool into arcs when illuminated.

It is not uncommon for equipment to be operated in field levels as high as 100 V/m. This translates into a power density of 26.5 W/m^2, which is only a little more than two orders of magnitude below the level producing spectacular effects.

A tragic example of the effects of HPM illumination on electronics is the event that occurred on the US aircraft carrier Forrestal on July 29, 1967. At that time, the Forrestal was cruising off the coast of North Vietnam. Its A-4 Skyhawk jets had flown more than 700 sorties. A number of A-4s were on the deck fully fueled and loaded with 1000-lb. bombs, air-to-ground missiles and air-to-air missiles. One of the missile cables apparently had a shielded connector that was improperly mounted. When illuminated by a shipboard radar, RF voltages developed in the degraded connector. This caused a missile to be fired across the deck, striking another aircraft. Secondary explosions of aircraft, bombs and missiles killed 134 men and did \$72 M of damage.

Despite this loss, there are a number of positive applications for HPM systems. Perhaps the most common is the high resolution radar. However, the primary application for the presented material is HPM weapon systems. Consequently, the reception analysis of HPM signals is limited to inadvertent reception and no attention is given to radar signal analysis or other similar radar operation concerns.

In order to be considered a viable source for HPM weapons, a device should provide an output power that exceeds 1 GW.[2] The output levels reported for HPM sources are steadily increasing. Presently, the largest peak power output reported for a single device is 15 GW. The largest single pulse energy that has been reported is less than 1 kJ. However, there are a number of projects underway where the investigators are hoping to develop a device capable of providing 1 kJ of energy in a single high power pulse. Generally, the greater output characteristics demand more bulk and weight in the device. Consequently, it appears that there are practical upper limits for single device output levels, namely 100 GW of power and 10 kJ of energy under single pulse operation.[3] With phase-locking, multiple sources can conceivably increase the single device levels to about 1 TW and 0.1 MJ, perhaps even higher.

In addition to the output levels, other factors should be considered for HPM sources. These include efficiency, bandwidth, frequency, size and tunability. The source should be stable in frequency (< 1 percent bandwidth) and should operate in the frequency range between 500 MHz and 12 GHz with an efficiency of 30 percent.[3]

If a weapon system is based upon the illumination of a target by an intense microwave fluence, HPM radiative propagation occurs. For exo-atmospheric propagation, there is essentially no energy absorption. In the atmosphere, there are significant loss mechanisms. When the target is located near the earth's surface, then atmospheric refraction and absorption must be considered. Also, ground reflection and surface diffractions may reduce significantly the illumination intensity.

When considering the interaction between a system and an HPM beam from a source at some distance away (compared to wavelength and illuminator antenna dimensions), there are various factors to be examined.[4] Accordingly, the maximum response is normally achieved by the use of highly resonant exciting waveforms, such as chip pulses and damped sinusoids. This allows quasi-CW concepts to be used so that the transfer functions can be considered functions of the dominant frequency of the exciting waveforms.

Normally, system tolerance to HPM is specified in terms of the incident power density, power per unit area of the microwave beam or in terms of the incident energy or fluence. In addition, the peak field strength also is important in producing effects within the illuminated system. For chip pulses, the fluence is the product of the average power density times the pulse duration. And for damped sinusoids, the flu-

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TABLE I
TISSUE PARAMETERS AT 1 GHz

Tissue	ε'_r	σ (Ω/m)
Muscle	49 to 52	1.27 to 13.3
Fat	5.3 to 7.5	0.83 to 1.49
Bone Marrow	4.3 to 7.3	0.43 to 1.00

ence is the quotient of the peak power density divided by the radian frequency of the HPM illuminator.

High Power Microwave Effects

Heating Effects

Microwave heating of dielectric materials is a well known process called dielectric hysteresis that is analogous to magnetic hysteresis in magnetic materials. Dielectric heaters are in widespread use in various industries to seal, emboss, dry and mold materials. These devices generate from hundreds to thousands of watts of RF power at 20 to 70 MHz. Moreover, their exposure fields exceed 200 V/m or 0.5 A/m, which corresponds to a power density of 11 mW/cm².[2]

The analysis of microwave bulk heating can be accomplished by introducing complex permittivity,

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1}$$

where

$$\varepsilon'' = \varepsilon' \tan\delta - \sigma/\omega \tag{2}$$

where

$\tan\delta$ = the loss tangent
σ = the conductivity of the material

The power absorbed into heat per unit volume is

$$p = (\omega\varepsilon' \tan\delta)\, E^2 + \sigma E^2 \tag{3}$$

E = the electric field strength of the microwave

Typically, ε' and ε'' are frequency dependent. Over very wide frequency ranges, materials may exhibit resonance absorption and associated permittivity changes due to molecular vibrational modes. The water molecule is an effective absorber of microwave radiation.

Electrical properties of human tissue at microwave frequencies have been studied extensively. According to the Kronig-Kramer relation, the relative complex dielectric constant $\varepsilon_r = \varepsilon/\varepsilon_0$, for general dielectric material is[5]

$$\varepsilon_r(\omega) = \varepsilon_h + \frac{\varepsilon_l - \varepsilon_h}{1 + j\omega\tau} \tag{4}$$

where

ε_h = the high frequency limit
ε_l = the low frequency limit
τ = the dielectric relaxation time

These may vary depending upon the type of biological tissue. Similarly, the conductivity is

$$\sigma(\omega) = \sigma_l + (\sigma_h - \sigma_l)\,\frac{(\omega\tau)^2}{1 + (\omega\tau)^2} \tag{5}$$

where

σ_h = the high frequency limit
σ_l = the low frequency limit

For skin tissue, appropriate parameter estimates are $\varepsilon_l = 42$, $\varepsilon_h = 4$, $\tau = 6.9$ ps and $\sigma_l = 1.4$ Ω/m.[6] Therefore, at 1 GHz, $\varepsilon_r = 41.9 - j1.64$ and $\sigma = 1.4$ Ω/m. Corresponding measured data agree quite well. Other types of tissue at 1 GHz are listed in Table 1.

Biological Effects

Most of the data on biological effects from HPM radiation are explained by thermal energy conversion, almost exclusively as an enthalpic energy (heating) phenomenon.[6,7] However, this does not provide a predictive model of the biological consequences of nonuniform absorption of energy in animals and humans. The nonuniform, largely unpredictable distribution of energy absorption may give rise to temperature increases and rates of heating that can result in unique biological effects. Furthermore, induced temperature gradients in deep body organs may act as a functional stimulus to alter the normal function both in the heated organ and in other organs of the system. Thus, indirect effects can be induced in organs far removed from the site of the initial energy absorption. It should also be pointed out that temperature increases from diverse etiologies may induce chromosomal alterations, mutagenesis, virus activation and inactivation, as well as behavioral and immunological reactions.

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The nonuniform pattern of microwave absorption, with differing rates of temperature rise at absorption sites, results in a pattern of heating that can not be replicated with radiant, convected or conducted heat. Therefore, experimental control groups may have limited value for temperature increases to discriminate between direct and indirect effects, or between effects due to temperature rise and those independent of it.

Microwave radiation can produce appreciable heating effects in animal and human tissues. For frequencies up to 10 GHz, a single-pulse fluence of 1 MJ/m^2 can produce significant heating. At higher frequencies, microwave absorption occurs near the body surface and results in significant heating at lower fluences. For example, at tens of gigahertz, a fluence of only 20 J/cm can burn the skin.

The brain is sensitive to heating effects. Microwave induced temperature increases of only a few degrees have caused convulsions, unconsciousness and amnesia in laboratory rats. Corresponding effects in humans would be expected at power densities of 10 to 50 mW/cm^2 under continuous exposure for frequencies below 10 GHz.

Overall, an increase in the total body temperature of 1°C from microwave radiation is considered to be harmful. Prolonged exposure to a great increase in temperature from microwave radiation can be fatal. At frequencies below 400 MHz and above 3 GHz, less than one-half of the incident energy on a human is absorbed. However, between 1 GHz and 3 GHz, the amount of incident energy absorbed approaches 100 percent, depending upon the skin thickness and the subcutaneous layers of fat. It has been found that pulsed power can induce biological effects not seen with CW power of the same average value. The maximum CW power density considered to be safe by the US government is 1 mW/cm^2 under unlimited exposure and 10 mW/cm^2 for exposure times less than one hour.

When human beings are exposed to pulsed microwave radiation, an audible sound can be perceived.[8] At times, the sound has been described as a click, buzz or chirp, depending on the pulse width and repetition rate. Pulses of 1 to 32 μs pulse width at a frequency of 2.45 GHz and fluences as low as 40 μJ/cm^2 have been heard as distinct clicks that appear to originate from within or immediately behind the head. The pulsed microwave energy is believed to induce a thermoelastic wave of pressure in brain tissue that drives the inner ear receptors via bone conduction. The presently available physiological data are not sufficient to permit a complete evaluation of the health risk to human beings.

Electrical Effects

Under microwave illumination, metal surfaces and wiring will have induced surface currents. In turn, wire currents will lead to termination

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voltages. When characterizing the electromagnetic coupling from the exterior of an electrical system to a specific interior point, a convenient parameter is the receiving cross section defined by

$$\sigma_R = \frac{P_L}{p^{inc}} \tag{6}$$

where

P_L = the power delivered to a load Z_L connected across the specified terminals
p^{inc} = the incident power density

A general form for the receiving cross section is[9]

$$\sigma_R = \frac{\lambda^2}{4\pi} \eta p q \, D(\theta,\phi) \tag{7}$$

where

λ = the wavelength
η = the ohmic efficiency
p = the polarization matching factor
q = the impedance matching factor
$D(\theta,\phi)$ = directivity

Using the maximum receiving cross section provides an upper bound on the power coupled to the interior terminals. It has been shown that for a set of interior terminals, the maximum power that can be coupled decreases with an increase in frequency.[9] This is somewhat misleading, since the efficient extraction of power from an electrically small antenna is very difficult because of the very small resistive part of the antenna impedance, the radiation resistance.

The computation of currents induced on wire structures at microwave frequencies becomes more difficult as the electrical length increases. Numerical studies of field-to-wire coupling for a few antenna configurations illuminated at microwave frequencies have been performed.[10] It was found that the wire currents were developed in a pattern consisting of standing waves and traveling waves where the peak currents tended to remain relatively constant as the frequency increased. Their results were obtained for cases where the direction of the incident microwave beam and the polarization were chosen to yield the greatest peak currents.

Microwave coupling to transmission configurations also has been measured. Since the wavelength is near the characteristic dimensions of typical transmission line configurations, special considerations are often required.

An experimental study of the power coupled to various transmission lines under illumination from 1 to 18 GHz has been performed.[11] Five wire types with horizontal and vertical illumination and three heights above a ground, three-eighths inch, two inch and infinite (over absorber material), were considered. The wire configurations included a bare wire (BW), a twisted pair (TP), a standard RG58 coaxial cable (SC), an optimum braid RG58 (OC) and a shielded, twisted pair (STP). With the incident illumination normalized to 1 mW/m^2, the maximum received power into 50 Ω terminations was –30 dBm for BW, –42 dBm for TP, –80 dBm for OC and –70 dBm for SC and STP. Usually, the received power was greatest at low frequencies (1 to 2 GHz), relatively insensitive to wire height ($<$ 8 dB variation) and greatest for vertical polarization.

Recently, the intrasystem electromagnetic compatibility analysis program (IEMCAP) was modified to treat field-to-wire coupling from 1 GHz to 40 GHz. The measured data was incorporated together with method of moments calculations. Results from the new algorithm appear to be much less conservative than those obtained from using transmission line approximation alone. The algorithm predicts that maximum coupling occurs for a line height of $\lambda/2$ and tends to hold that level of coupling for greater wire heights. This saturation coupling level decreases with frequency as 1/f.

There is a discrepancy between these reported results[11,12] on how the microwave coupling to wires depends upon the wire height. This may be explained in part by the difficulty in obtaining accurate measurements for the low level signals in determining the variation of the received power with wire height.

Effects on Electronics

Once microwave energy reaches a target, a sequence of penetration and propagation processes will take place from the target's outer surface into its interior and ultimately arriving at its electronics. The energy of arrival can be affected via either front-door or back-door paths. A front-door path is referred to as an intended path for microwave transmission and reception. An example of this is an antenna that is connected to a coaxial cable terminating at an electron box. A back-door path is an inadvertent point of entry for energy penetration, such as windows, doors, cracks, seams, connectors, cable shields or nonelectrical lines.

For electronics under microwave illumination, rectification is usually the principal mode by which the microwave energy is coupled into the system electronics. It is the cause for computer malfunction under radar illumination, for erroneous output from an EKG when a physician's paging system is activated or for a stereo system to receive a citizen's band (CB) signal. It is also because of rectification that warnings are posted for heart pacemaker interference from microwave ovens and airport radar transmitters.

Generally, microwave energy coupling via rectification occurs by the signal entering a victim amplifier or digital circuit through interconnecting signal and/or power cables and sometimes is enhanced by parasitic resonances. A typical response is then characterized by the microwave signal being propagated to a nonlinear device. The resulting nonlinear response produces a video pulse or a wideband signal, which propagates throughout the electronic system, upsetting the normal data transmission and storage. In some cases, the produced pulse or signal may cause damage to system components.[13]

Intermodulation is a phenomenon associated with electromagnetic interference (EMI). It arises from the simultaneous operation of two or more sources with nonlinear elements located either in the victim's response circuits, the transmitters or the propagation path.[14]

An example of severe intermodulation interference problems has occurred aboard ships.[15] Here, the interference results from electromagnetic scattering from metallic structures, such as ladders, life-raft

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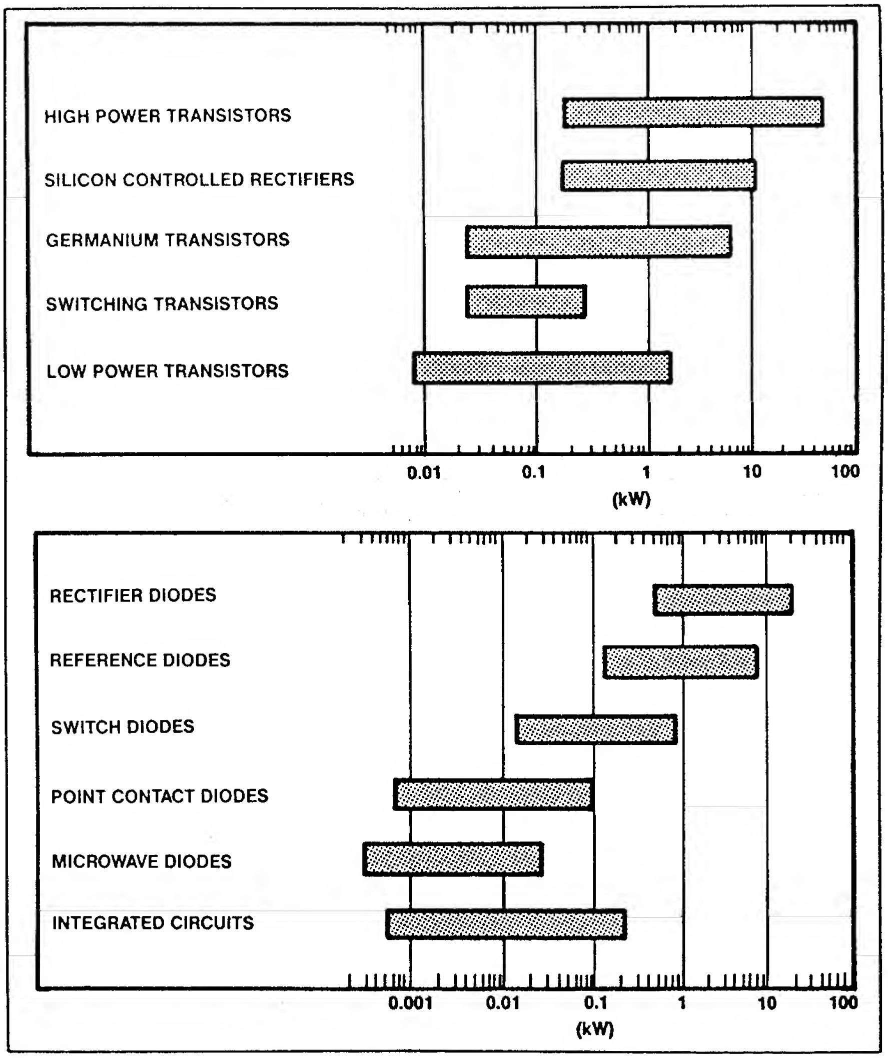

Fig. 1 Typical ranges of damage threshold levels for devices.

rangers, guard rails, antenna guying wires, booms and anchor chains, where oxidized metal-to-metal joints develop junction diodes. As a result, significant intermodulation product signals are generated.

A latch-up is the condition where a semiconductor device no longer responds to an input. In some cases, latch-up may lead to the destruction of the device as occurs in complementary metal oxide semiconductor (CMOS) circuits. There are a number of preventative measures that can make devices less sensitive.

Generally, the latch-up state arises from a parasitic transistor condition that occurs in IC fabrication. An inadvertent multijunction SCR-type switch is formed, either a PNPN or a NPNP. When the switch is triggered, the device is disabled. Possible sources of latch-up include minority carriers injected into the substrate by a transient forward bias on parasitic PN junctions, photoelectric generation from ionizing radiation and impact generation from thermal heating.

A major failure mechanism for semiconductor devices under a short pulse stress is thermal second breakdown. The first breakdown, which occurs in the reverse bias configuration, is an avalanche breakdown that is associated with the Zener diode. As the current is increased in the reverse bias configuration, the second breakdown, a destructive-irreversible process, occurs.

Thermal second breakdown is a result of heating in the junction region. Second breakdown is thought to be a filamentation process that occurs in three stages, including

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nucleation of the filament, the growth of a relatively broad filament across the depletion region and the growth of a second filament of molten material within the first filament. The filamentation growth begins in a region of high current density and more than one filament may occur. With the formation of the filament of molten material, the device is irreversibly damaged.

The occurrence of thermal second breakdown for a video pulse depends upon the stress pulse width and average power. For pulse widths in the range of 10 ns to 100 μs, the damage threshold power P_D required for thermal second breakdown is[16]

$$\frac{P_D}{A_J} K\tau^{-1/2} \qquad (8)$$

where

A_J = the junction area
τ = the pulse width
K = the proportionality constant, the K-factor

The K-factor is characteristic of the device. Since breakdown may occur over only a fraction of the junction area, one tenth of the junction area is often used for A_J in Equation 8 for bounding purposes.

The device K-factor can be computed from product data or it can be measured.[16] Moreover, significant device-to-device variation in the K-factor may occur because of the nature of a breakdown process. Typical ranges of damage threshold levels for devices are shown in Figure 1. The damage threshold power is expressed in units kW for 1 μs rectangular pulse stress.[17] According to these data and Equation 8, the damage threshold power may be as low as 1 W for microwave diodes or as large as 160 kW for high power transistors under a 100 ns rectangular pulse stress.

For a very short stress pulse, < 100 ns, the thermal process causing damage is adiabatic. In this case, damage occurs before the absorbed heat is conducted away from the junction region. Consequently, the energy available to cause damage is proportional to τP_D. For long stress pulses > 100 μs, the thermal stress producing damage approaches the constant power rating that is provided in the manufacturer's specifications for the device.

TABLE II
THRESHOLD POWER FOR DAMAGE MEASURED FOR ICs

Device	Type	Failure Power (W) Input Lead	Output Lead	Battery Lead
Fairchild 9930	Dual 4-Input Gate	730	290	660
Signetics SE 8481	Quad 2-Input Nand Gate	230	149	1230
TI 946	Quad 2-Input Nand Gate	50	60	870
Sylvania SG140	Quad 2-Input Nand Gate	170	210	660
Motorola MC301G	5-Input Gate	2020	950	4400
Radiation Inc. 709R	Operational Amplifier	50	57	206
Motorola MC1539G	Operational Amplifier	890	15000	5400
TI 709L	Operational Amplifier	1600	11000	8400
Radiation Inc. RD211	Dual Quad-Diode Gate Expander	63	63	—
Radiation Inc. RD220	Hex Inverter	110	430	1080
Radiation Inc. RD221	Dual Binary Gate	850	570	2180
Radiation Inc. RA239	Amplifier	—	160	210
Philbrick Q25AH	Hybrid Amplifier	630	50	1000
Philbrick Q25AM	Hybrid Amplifier	320	6300	3200
Fairchild MA709	Operational Amplifier	35	95	—

Combining all three of the foregoing failure mechanisms into a single relationship yields

$$\frac{P_D}{A_J} \sim K' \sqrt{A_J}\,\tau^{-1} + K\tau^{-1/2} + \frac{K''}{\sqrt{A_J}}\tau^{0} \qquad (9)$$

where the proportionality constants K' and K" are characteristic of the specific device.[16]

In this paper, only discrete devices have been considered. Integrated circuits consist of a number of devices with a large number of PN junctions. However, after testing a number of ICs, it appears that the damage threshold powers for stress pulse widths of 100 ns to 100 μs appear to follow Equation 8 dependence on pulse width. Table 2 provides damage threshold powers measured for a few ICs. These data are normalized for a 100 ns pulse width.

Measurements of the damage threshold power for various devices under microwave pulse excitation have been performed.[13] The results indicate that power levels required for device damage are typically near 100 W for 1 μs pulses at frequencies of a few GHz. Using Equation 8 to estimate the dependence on pulse width would indicate threshold power levels of 320 W are needed for 100 ns pulses. This result is consistent with the data presented in Table 2.

In the fabrication on integrated circuits, multiple PN junctions are normal occurrences. When the PN junction is reversed biased, the depletion region expands with the increase in voltage. If the depletion region expands to another junction, then the resulting current may be sufficiently large to damage the junction, producing what is called punch-through.

Advanced VLSI/VHSIC digital devices using either bipolar or CMOS technology have shown to be highly susceptible to upset (change in stored or transmitted information), as well as damage when HPM illumination is directed upon the chip or multichip package.[3] These devices utilize submicron dimensions and operate at clock rates of up to 100 MHz with logic levels of 3.3 V. As device dimensions and logic levels correspondingly decrease, device sensitivity to HPM increases.

Test results from HPM testing of various analog and digital devices show that the microwave power that is required to cause upset in a digital device is more than that required to cause disturbance in an analog device.[13] Moreover, the test results do not vary significantly between devices. The power levels required for burnout/damage generally are several orders of magnitude higher than the levels required for causing degradation in the performance of analog devices. Damage threshold levels for digital devices are only

slightly lower than those required for analog devices.

The extent of computing equipment susceptibility to microwave radiation has been studied.[18] Both microprocessors and small computers were irradiated in a mode-tuned chamber and occurrences of digital circuit upset were sought. A simple program to read into and fetch from RAM memory was executed as the device was being continuously illuminated by microwaves. With each memory fetch, there was a check to see if the recalled number had been affected by the radiation. A changed number indicated that an upset had occurred. In some cases, the effect exhibited a wild-running display. The maximum field strength of the test was 200 V/m (RMS), corresponding to an incident average power density of 10.6 mW/cm.[2]

Irradiation of several unshielded microprocessors and small computers, including the TRS-80 and the ZX81, indicated that upsets for microwave frequencies in the range of 1 GHz to 10 GHz were rare. With the arrival of faster microprocessors and small computers operating at clock rates in the tens of MHz, more upsets are expected for frequencies above 1 GHz. For the KIM-1 microprocessor, the most susceptible in the test, there were upsets observed for field strengths as low as 2 V/m (RMS) and incident average power density of 106 $\mu W/cm^2$.

One of the electronic components most sensitive to microwave burnout is the microwave detector diode with burnout thresholds as low as 1 μJ.[19] A lower bound on the vulnerability of hardware to front-door coupling can be obtained by considering a microwave receiver in which the microwave energy is received by a three-meter antenna with a 70 percent aperture efficiency. Accordingly, the single pulse fluence that would burn out the detector diode is

$$\frac{P_r \tau}{A_{em}} = 0.2\ \mu J/m^2 \tag{10}$$

where

P_r = the maximum received power

A_{em} = the maximum effective area for the antenna

τ = the pulse duration

For 100 ns pulse, the corresponding peak electric field strength that causes bit errors varies from 9 to 90 V/m.

A corresponding bound on back-door coupling can be obtained by testing the equipment that is the most sensitive to microwave interference. It has been shown that unshielded computers suffer bit errors when exposed to microwave fluences as low as 10^{-7} to 10^{-8} mJ/cm^2 at 1 GHz.[19] The fluence level required for bit errors is higher at higher frequencies.[20]

Hardening against High Power Microwave Illumination

Shielding

The electromagnetic barrier is a closed surface about the victim that excludes the effects of all sources outside the barrier.[21] Alternatively, the barrier may be a closed surface that confines the electromagnetic effects of the source to the enclosed volume. Source-confining barriers have long been used to enclose noisy equipment, such as rectifiers and high power transmitter RF amplifiers. Barriers designed to exclude the effects of external sources are also common. The excluding barrier may be used to protect equipment even when the number and location of the microwave sources are not well known.

A closed, superconducting shield is a perfect electromagnetic barrier, since all electromagnetic waves are completely excluded or confined by this shield. Also, closed shields of common metals are very effective in excluding most electromagnetic waves. However, practical shields can not be closed surfaces. They have openings to transfer information, supply energy to the interior equipment and remove waste heat. A practical shield is an incomplete barrier because it allows virtually unlimited interference penetration along wires and apertures penetrating the shield. This is true even if the wire is connected to a ground wire. The ground wire can be a path for interference penetration.

Aperture penetration through an electromagnetic shield decreases with distance from the aperture as $(r/a)^{-3}$, where a is the characteristic dimension of the aperture.[22] Inside the aperture, the field is essentially the incident field. In the mid and high frequency regimes, the aperture may be considered an aperture receiving antenna.

Conductive penetrations refer to signals propagated along conductors that penetrate the electromagnetic barrier. There are three primary techniques to eliminate or at least reduce conductive penetrations, including filtering, extending the barrier and dielectric isolation.

Filters

At each point where a conductor, such as a power line, must penetrate a topological layer of shielding, a filter should be inserted. For microwave protection, in most cases, the filter is lowpass. Generally, lowpass filters operating at 500 MHz and below are built with inductive coils and capacitors. At higher frequencies, filters are usually formed by distributed circuit elements, that is, segments of transmission lines.

Often, a simple method of reducing conductive penetrations in the 30 MHz to 1 GHz region is to employ feedthrough capacitors. This method can be implemented at the connector where a capacitance to ground is applied at each pin of the connector. In practice, typical obtainable attenuation is about 10 to 30 dB in the frequency range from 30 MHz to 300 MHz, depending upon the value of the capacitance and a good ground connection. Additional attenuation is provided through ferrite beads in combination with the feed-through capacitor.[23]

There are a number of multi-element lowpass filter designs that can be implemented. Common configurations include the T, L and π circuits. If the load and source impedances are not matched, then the L filter should be used with the inductor facing the low impedance. If the source and load impedances are both small, then a T filter is recommended. For high impedance circuits, the π filter is recommended.

Better filter performance at microwave frequencies can be achieved through the use of distributed-element components. This design is intended for implementation within the connector housing where the center conductors are the individual pin connections. A comparison of the insertion losses typical for a lumped-element lowpass filter design and a distributed-element de-

sign shows that the stop band extends well into the microwave frequency region.[24,25]

High Power Microwave Weapons

Whether or not high power microwave beams can be used as a weapon is based not only on technical issues, but also on economic considerations.[19,26] From the technical side, it is clear that fluences greater than 270 $\mu J/m^2$ with 100 ns pulse widths can be produced at 20 miles from a 1 GHz source with today's technology. This level of radiation intensity probably will not produce biological effects. However, the effects on unprotected electronics may be substantial. Fluence levels, power densities and field strength that appear to be possible with today's technology are listed in Table 3. With the projected development of new techniques, the radiated power densities may be increased by a factor of 100 and the fluence levels may be increased by a factor of 10^4 to levels that may affect biological targets at large distances. In addition to the conventional sources, it has been suggested that a nuclear weapon design could be implemented that would develop HPM fluences.[27]

TABLE III

NOMINAL FLUENCE, POWER DENSITY AND ELECTRIC FIELD STRENGTH ALONG THE BORE SIGHT FROM A 10 GW/100 ns/1 GHz SOURCE WITH 1 100 m^2 DISH REFLECTOR ANTENNA WITH 50 PERCENT APERTURE EFFICIENCY

Distance	Fluence	Power Density	Electric Field Strength
100 m	28 J/m^2	560 MW/m^2	460 kV/m
1 km	0.28 J/m^2	5.6 MW/m^2	46 kV/m
5 km	11 mJ/m^2	220 kW/m^2	9 kV/m
10 km	2.8 mJ/m^2	56 kW/m^2	4.6 kV/m
32 km	270 $\mu J/m^2$	5 kW/m^2	1.4 kV/m

The economic considerations arise in evaluating the cost of deploying HPM weapons vs. the adversary's cost of hardening against the HPM threat. A program to implement retrofit hardening of existing weapon systems to a microwave threat may be exorbitant in cost.

A weapon that disables electronic systems is an attractive concept. Modern weapons employ extensive electronics for delivery and control. Consequently, disabling the electronics will probably render the adversary's weapon system harmless or at least ineffective. Unless a significant effort is made toward protecting a system, it will essentially have no degree of protection. A significant effort in protecting a system involves continuous barriers with filter isolation for each conductive penetration.

Conclusion

In recent years, significant advances in producing high power microwaves have been achieved. The applications of these technologies include communications, high resolution radar and next generation linear accelerators. In this article, various HPM effects on electrical systems, electronics and biological targets were presented.

As the incident fluence is increased, the degree of required protection becomes more difficult to achieve. Providing an adequate level of protection for an already existing system may be expensive as well as difficult. A complete electromagnetic barrier, or perhaps more than one, will be required. This in turn requires hardening apertures and filtering conductive penetrations at each barrier surface. Normal corrosion and wear can seriously deteriorate the shielding integrity.

In general, it has been shown that HPM has the potential of being a threat to electronic systems. Also, it has shown that protective measures exist. However, these protective measures are difficult and costly to implement and maintain. ■

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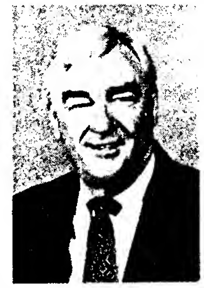

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